Fine-scale factors influence fire regimes in mixed-conifer forests on three high mountains in Mexico

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\textbf{Abstract.} We investigated the influence of broad- v. fine-scale factors on fire in an unusual landscape suitable for distinguishing the drivers of fire synchrony. Our study was conducted in the Sierra Madre Oriental mountain range, in north-eastern Mexico. We worked in nine sites on three parallel mountains that receive nearly identical broad-scale climatic influence, but between which fires are unlikely to spread. We collected and cross dated samples from 357 fire-scarred trees in nine sites in high-elevation mixed-conifer forests and identified fire dates. We used Jaccard similarity analysis to evaluate synchrony among sites and quantified relationships between climate and fire occurrence. Fires were historically frequent (mean fire interval ranged from 8 to 16 years in all sites) and dates of fire exclusion ranged from 1887 to 1962. We found low fire synchrony among the three mountains, indicating a strong influence of fine-scale factors on fire occurrence. Fire regime attributes were similar across mountains despite the independence of fire dates. La Niña events were associated with fire over time, although not significantly since the 1830s. Our results highlight the importance of scale in describing fire regimes and suggest that we can use fire history to understand controls on complex ecosystem processes and patterns.

\textbf{Additional keywords:} climate, dendrochronology, fire history, fire synchrony, Sierra de Arteaga, Sierra Madre Oriental.

Received 17 December 2013, accepted 9 May 2014, published online 11 September 2014

\textbf{Introduction}

Factors that affect fire occurrence operate on a continuum of scales, from fine-scale microsite variation in fuels and topography to broad-scale global climate oscillations. Fine-scale factors interrupt fire synchrony and create heterogeneity across landscapes, whereas broad-scale factors are influential in synchronising fire across landscapes and even continents. The relative importance of broad-scale and fine-scale controls on fire regimes depends on the scale of analysis and on the strength of the influences in a given area (Falk et al. 2007; Kellogg et al. 2008). Climate is a significant broad-scale driver of wildfire synchrony at regional to continental scales (e.g. Swetnam and Betancourt 1990; Taylor and Beaty 2005; Kitzberger et al. 2007; Heyerdahl et al. 2008). Synchronous regional fire years, in which widely separated sites burn in the same year, can result from periods of widespread drought associated with regional-scale climate patterns, as illustrated in the south-western USA by high synchrony across mountain ranges separated by deserts (Swetnam and Baisan 2003).

Fine-scale variation in factors such as ignitions, topography, and fuel type, amount and connectivity may reduce synchrony in fire between sites because they exert independent influence on a site-by-site basis, increasing heterogeneity in burn patterns (Brown et al. 2001; Kellogg et al. 2008; Iniguez et al. 2009; Ireland et al. 2012). Controls may shift depending on the relative strength of forcing factors. Fine-scale topographic influences, for instance, may be stronger in years with mild climate, but severe fire weather can override local factors and result in
widespread synchrony of fire occurrences (Taylor and Skinner 2003; Flatley et al. 2011).

Human activity has been described as a broad-scale influence on fire (Brown et al. 2001). For example, large areas of the south-western USA were affected by humans between 1870 and 1900 when surface fire regimes were interrupted due to the introduction of livestock, logging, predator control, land use changes and fire suppression (Swetnam and Baisan 2003). However, human influences can also be expressed at more local scales. Although fire regimes in Mexican forests have received limited scientific attention (Rodríguez Trejo 2008), studies in Mexico have documented sites that experienced fire exclusion at different points throughout the twentieth century or not at all (e.g. Fulé and Covington 1999, Stephens et al. 2003, Poulos et al. 2013).

Our understanding of the scales at which fine- and broad-scale factors influence fire occurrence is incomplete, although several studies have examined controls on fire at multiple scales (Falk et al. 2007). For example, Heyerdahl et al. (2001) explored influences on variations in fire regimes within and among watersheds and concluded that historically, both broad-scale factors such as regional climate and fine-scale factors such as aspect and elevation influenced fire frequency, size and season in the interior western USA. Livestock grazing and fire suppression became the most important influences on fire occurrence in the twentieth century. Similarly, Hessl et al. (2004) found that in the state of Washington, climate (summer drought and the positive phase of the Pacific Decadal Oscillation) was linked to fire, but these relationships were overriden by land use changes in the twentieth century. In another example from the Klamath Mountains, variation in fire frequency was related to aspect. Topographic features that acted as barriers to fire spread were important in defining spatial patterns of fire on the landscape except during years of exceptional climate, when more extreme fire behaviour overcame barriers to fire spread that operated in more moderate conditions (Taylor and Skinner 2003).

Various studies have also explored the controls on fire using models. Parisien et al. (2010) found in a modelling exercise that weather-related variables had a larger effect on mean burn probability, whereas fuels and ignitions had a larger effect on the variability of burn probability. However, the authors noted that cleanly separating broad-scale and fine-scale factors is not possible. Other modelling exercises have demonstrated that broad-scale controls are more important in topographically simple landscapes, whereas fine-scale controls are more important in topographically complex landscapes (Kellogg et al. 2008; Kennedy and McKenzie 2010).

El Niño-Southern Oscillation (ENSO) is a significant broad-scale influence on fire in many parts of North America and globally. The phases of ENSO affect winter precipitation and thereby fire differently in different regions of North America. La Niña is associated with drought and increased fire activity in the south-eastern USA and northern Mexico. The present study site is located close to the dipole in central Mexico where the effects of ENSO phases switch and La Niña brings wetter conditions (Caso et al. 2007, Yocom and Fulé 2012). In a previous fire-climate study at Peña Nevada in north-eastern Mexico, Yocom et al. (2010) found patterns of frequent fire and a strong relationship between drought and fire years. At this site, the relationship between ENSO and fire changed over time. Before the 1830s, La Niña events were strongly associated with fire occurrence, but the relationship disappeared after the 1830s and in recent years fires have burned at Peña Nevada during both strong El Niño and La Niña events. It is unknown whether this unstable relationship is unique to Peña Nevada or whether the relationship between ENSO and fire has become disassociated in other parts of northern Mexico as well.

The Sierra Madre Oriental is a region rich in biodiversity and endemic species, with 50 gymnosperm species, 10 of those endemic (Contreras-Medina and Luna-Vega 2007). The northern end of the Sierra Madre Oriental is called the Sierra de Arteaga. The area is useful as a ‘natural experiment’ to investigate the relative influences of broad-scale and fine-scale controls. This part of the Sierra consists of a series of east-west-oriented, high, parallel, forested mountains separated by deep, non-forested valleys used for settlements and agriculture (Fig. 1). The distinctive topography allowed us to examine fire patterns in sites on mountains separated by only ~10 km. Because the mountains are in such close proximity, they experience the same broad-scale climatic influences such as ENSO and regional drought. However, we can assume that fires on individual mountains come from separate ignitions because surface fires would be unlikely to cross between them due to topography and vegetation patterns. Quantifying fire synchrony among mountains thus allows us to differentiate between broad-scale and fine-scale controls on fire regimes. Broad-scale influence would be indicated by high fire synchrony among mountains, suggesting that climate events strongly affect fire occurrence. Fine-scale control would be indicated by highly asynchronous fire occurrence among mountains, suggesting that fine-scale factors are more important in determining the occurrence of fire. Intermediate levels of synchrony would indicate combinations of controlling factors at a given scale.

Our objectives were to (1) characterise the historical fire regime of each mountain and describe the occurrence of low-severity and high-severity fire in our sites; (2) assess the relative influence of broad-scale and fine-scale factors by quantifying synchrony of fire dates among sites and mountains, and (3) determine the influence the ENSO on fire occurrence, and assess the stability of the relationship over time.

Methods

Study area

We sampled sites on three different mountains: San Antonio (southernmost), La Viga (middle) and Rancho Nuevo (northernmost; Fig. 1). Average elevation of sites ranged from 3081 to 3464 m and average slope ranged from 22 to 52% (Table 1). San Antonio sites were dominated by a mixture of Abies vejarii (Martínez), Pinus hartwegii (Lindl.), and P. strobiformis (Engelmann); La Viga sites were dominated by P. hartwegii; and Rancho Nuevo sites were dominated by Pseudotsuga menziesii (Mirb.) Franco with a large amount of A. vejarii in the understory (Farjon 1990; Farjon and Styles 1997). We also found small pockets of P. culminicola (Andresen & Beaman), an endangered pinyon pine endemic to the Sierra Madre Oriental, as well as isolated populations of Populus tremuloides (Michx.),
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and *Quercus* and *Praunus* spp. The vegetation on the non-sampled south-facing slope of each mountain was quite different, being dominated by shrubs. The mountains in this region are the result of uplift and folding and the exposed rock is limestone (Ferrusquia-Villafranca 1993). Weather data from the closest weather station, San Antonio de las Alazanas (25°16’N, 100°37’W), near our study sites but at a lower elevation (2170 m), indicated an average yearly temperature of 13°C and average yearly precipitation of 499 mm (1955–1998; data extracted from the ERICIII database, IMTA 2006). Summer precipitation (June–August) accounted for 43% of the precipitation. Applying the dry adiabatic lapse rate of 9.8°C per 1000 m in elevation, yearly average temperature at our sites was estimated at 1–3.5°C. Currently, there are small centres of human population in the valleys between mountains, and roads lead to the top of each mountain. Forests in this area have been used for centuries by local people for timber, fuelwood and resin production (Ortega-Jiménez 2008). Fire suppression efforts began in earnest with the publication in 1930 of regulations organising the suppression of wildfires in this region (Ortega-Jiménez 2008).

### Field sampling

An initial collection of fire-scarred tree samples was made at one of the San Antonio sites in 2001 as part of the North American Dendroecological Fieldweek (Speer et al. 2006). The remaining collections were made in 2007 and 2008. We established three sites on each mountain, for a total of nine sites. Sites on San Antonio are referred to as SA1, SA2 and SA3; La Viga sites are LV1, LV2 and LV3; and Rancho Nuevo sites are RN1, RN2 and RN3. On each mountain, study sites of 25 ha each were spaced at a minimum of 0.5 km and a maximum of 2 km apart. Sites were selected based on the presence of old trees or old remnant wood, in an effort to compile the longest possible tree-ring record. In each site, using chainsaws, we primarily sampled dead trees of any species that appeared in the field to have the largest numbers of well-preserved fire scars (Van Horne and Fulé 2006; Farris et al. 2013). We also sampled some live trees, which often had few scars, to ensure that the fire history extended up to the present. We collected 383 fire-scarred samples in total, most from pines (*P. hartwegii* and *P. strobiformis*) and a minority from *Pseudotsuga menziesii* and *A. vejarii*.

### Laboratory methods

After surfacing samples, we cross dated them using a local *Pseudotsuga menziesii* tree-ring chronology (Villanueva-Díaz et al. 2007). The cross dating of a 10% subset of the samples was confirmed by a second dendrochronologist. We also measured the ring widths of each sample and checked the cross dating with the COFECHA software program (Holmes 1983). We identified fire scars to the exact year of formation by noting the cross dated ring in which the fire injury occurred (Baisan and Swetnam 1990). When possible, we determined the position of fire scars within rings for seasonal evaluation. We assigned dormant-season fires to the subsequent calendar year, which corresponds to observed seasonality of fire occurrence in the region.

### Analysis

To quantify historical fire frequency, we calculated surface fire interval distributions for periods in which there was an adequate tree-ring record in each site, defined as beginning in the first fire year when at least three samples in that site were recording (Table 1). Recording trees are those that have been scarred at least once previously and are more likely to scar in subsequent fires. The period of fire interval analysis for each site ended on the last year when at least three samples were scarred in order to describe the historical fire regime before fire exclusion in the
19th or 20th centuries. The only exception to this procedure was for one site on Rancho Nuevo: although eight samples were scarred in 1982, this fire followed an unusually long period of 73 years without a fire that scarred more than one tree; this interval was not included in the analysis of fire intervals because it probably reflected human modification of the fire regime. To assess the possibility of historical high-severity fire occurrence, which would have killed trees and opened up growing space for seedling establishment (e.g. Veblen et al. 1994), we identified periods in each site with multiple trees recruiting, by identifying pulses of regeneration (multiple trees with pith dates clustered in 30-year periods).

We calculated fire interval statistics with FHX2 ver. 3.2 software (Grissino-Mayer 2001). For each site, we calculated the composite mean fire interval (MFI) between all fires (hereafter referred to as ‘all fires’), and also between fires that scarred at least 25% of recording trees (‘widespread fires’). We used the Kolmogorov–Smirnov goodness-of-fit test \( z = 0.05 \) to determine whether the Weibull median probability intervals (WMPI) fit the data adequately. The WMPI is the fire interval associated with the 50% exceedance probability of a modelled Weibull function fit to an empirical fire interval distribution (Grissino-Mayer 2001). We used Tukey’s honest significant difference test \( z = 0.05 \) to determine whether there were differences in MFIs among sites and among mountains.

To test whether fires occurred synchronously among sites and among mountains more often than would be expected by chance, we used Chi-square tests. To compare synchrony of fire among mountains, we compared observed \( S_j = a - [a + b + c] \) for each \( m,n \) pair of sites for their period of common record, where \( a = \) the number of fire years in common between two sites, and \( b \) and \( c = \) number of years unique to one site or the other. The Jaccard coefficient is preferred for fire history analysis because it excludes the large number of (0,0) cases (i.e. non-fire years in both sites), which tend to inflate similarity values because most years are non-fire years. We used the resulting pairwise Jaccard distance \((1 - S_j)\) matrix to drive a divisive clustering algorithm (Jain et al. 1999) based on shared fire history.

To evaluate the influence of ENSO on fire occurrence at our study sites, we used superposed epoch analysis (SEA) in FHX2 (Grissino-Mayer 1995) to compare ‘widespread’ fire occurrence with an independently derived ENSO index. The SEA compared reconstructed December–February NINO3 values (1408–1978; Cook 2000) during fire years, 5 years before fire years, and 2 years after fire years. To address temporal autocorrelation in the NINO3 index, we fit autoregressive integrated moving average models based on lowest Akaike’s information criterion and significant but uncorrelated parameter estimates (Brown et al. 2008a) and used the resulting white noise residuals in our analyses. To assess statistical significance of the SEA results, we calculated 95% confidence intervals using bootstrapped distributions of climate data in 1000 trials. We analysed ENSO association with fire before 1831 and after 1832 to evaluate whether the relationship changed at the same time that the ENSO–fire relationship changed 200 km to the south at Peña Nevada (Yocom et al. 2010). We also analysed ENSO association with years in which zero, one, two or all three mountains recorded fire.

### Results

#### Fire regime

We were able to cross date 357 (93.2%) of the samples; 26 could not be cross dated. The earliest fire scar identified was from 1422 and the last fire scars formed in 1998. Of the fire scars where intra-ring position could be determined, 88% were formed in the dormant season and 7% were found in earlywood.

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**Table 1. Characteristics and fire scar information for nine forested sites sampled in the northern Sierra Madre Oriental, Mexico**

<table>
<thead>
<tr>
<th>Mountain</th>
<th>Code</th>
<th>Site</th>
<th>Average elevation (m)</th>
<th>Average slope (%)</th>
<th>Average aspect</th>
<th>Samples dated</th>
<th>Number of fire scars</th>
<th>First fire scar recorded (year)</th>
<th>Period of fire interval analysis (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Antonio</td>
<td>SA1</td>
<td>La Armenia</td>
<td>3270</td>
<td>41</td>
<td>SW</td>
<td>39</td>
<td>248</td>
<td>1572</td>
<td>1614–1918</td>
</tr>
<tr>
<td></td>
<td>SA2</td>
<td>Las Bateas</td>
<td>3253</td>
<td>22</td>
<td>SW</td>
<td>29</td>
<td>141</td>
<td>1566</td>
<td>1648–1887</td>
</tr>
<tr>
<td></td>
<td>SA3</td>
<td>Las Manzanas</td>
<td>3253</td>
<td>22</td>
<td>S</td>
<td>22</td>
<td>80</td>
<td>1572</td>
<td>1666–1962</td>
</tr>
<tr>
<td>La Viga</td>
<td>LV1</td>
<td>La Viga</td>
<td>3463</td>
<td>34</td>
<td>N</td>
<td>54</td>
<td>200</td>
<td>1422</td>
<td>1654–1917</td>
</tr>
<tr>
<td></td>
<td>LV2</td>
<td>Musgoso</td>
<td>3414</td>
<td>52</td>
<td>N</td>
<td>42</td>
<td>159</td>
<td>1696</td>
<td>1696–1917</td>
</tr>
<tr>
<td></td>
<td>LV3</td>
<td>Paraı ´so</td>
<td>3286</td>
<td>46</td>
<td>N</td>
<td>44</td>
<td>150</td>
<td>1557</td>
<td>1709–1917</td>
</tr>
<tr>
<td>Rancho Nuevo</td>
<td>RN1</td>
<td>Rancho Nuevo</td>
<td>3140</td>
<td>35</td>
<td>N</td>
<td>48</td>
<td>135</td>
<td>1610</td>
<td>1729–1909</td>
</tr>
<tr>
<td></td>
<td>RN2</td>
<td>El Tarillal</td>
<td>3081</td>
<td>47</td>
<td>NE</td>
<td>31</td>
<td>122</td>
<td>1666</td>
<td>1755–1909</td>
</tr>
<tr>
<td></td>
<td>RN3</td>
<td>Puerto El Tarillal</td>
<td>3211</td>
<td>44</td>
<td>N</td>
<td>48</td>
<td>122</td>
<td>1622</td>
<td>1710–1952</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td>357</td>
<td>1357</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 2. Measures of fire frequency in nine sites in the Sierra Madre Oriental, Mexico

Fire intervals are for fire dates recorded at each site during each site’s period of analysis. ‘All fires’ refers to any fire regardless of size, and ‘widespread fires’ refers to fires that scarred ≥25% of recording trees. WMPI, Weibull Median Probability Interval

<table>
<thead>
<tr>
<th>Site</th>
<th>Number of intervals</th>
<th>Mean fire interval: all fires (years)</th>
<th>WMPI: all fires (years)</th>
<th>Mean fire interval: widespread fires (years)</th>
<th>Minimum fire interval (years)</th>
<th>Maximum fire interval (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SA1</td>
<td>39</td>
<td>7.8</td>
<td>6.7</td>
<td>12.7</td>
<td>1</td>
<td>28</td>
</tr>
<tr>
<td>SA2</td>
<td>25</td>
<td>9.6</td>
<td>7.9</td>
<td>14.1</td>
<td>1</td>
<td>29</td>
</tr>
<tr>
<td>SA3</td>
<td>23</td>
<td>12.9</td>
<td>11.4</td>
<td>17.4</td>
<td>2</td>
<td>32</td>
</tr>
<tr>
<td>LV1</td>
<td>16</td>
<td>16.4</td>
<td>13.9</td>
<td>23.9</td>
<td>2</td>
<td>47</td>
</tr>
<tr>
<td>LV2</td>
<td>14</td>
<td>15.8</td>
<td>11.1</td>
<td>27.6</td>
<td>1</td>
<td>79</td>
</tr>
<tr>
<td>LV3</td>
<td>19</td>
<td>11.0</td>
<td>9.0</td>
<td>16.0</td>
<td>1</td>
<td>37</td>
</tr>
<tr>
<td>RN1</td>
<td>14</td>
<td>12.9</td>
<td>12.0</td>
<td>13.9</td>
<td>3</td>
<td>28</td>
</tr>
<tr>
<td>RN2</td>
<td>12</td>
<td>12.8</td>
<td>12.3</td>
<td>15.4</td>
<td>4</td>
<td>24</td>
</tr>
<tr>
<td>RN3</td>
<td>25</td>
<td>9.7</td>
<td>8.7</td>
<td>20.2</td>
<td>1</td>
<td>19</td>
</tr>
</tbody>
</table>

Fire intervals are for fire dates recorded at each site during each site’s period of analysis. ‘All fires’ refers to any fire regardless of size, and ‘widespread fires’ refers to fires that scarred ≥25% of recording trees. WMPI, Weibull Median Probability Interval.

MFI for ‘all fires’ ranged in individual sites from 7.8 to 16.4 years (Table 2). The Weibull function fit the data adequately in every site; WMPI ranged from 6.7 to 13.9 years. For ‘widespread fires’, MFI per site ranged from 12.7 to 27.6 years. Minimum fire interval in sites ranged from 1 to 4 years and maximum fire interval ranged from 19 to 79 years. On average, MFI and WMPI for ‘all fires’ and for ‘widespread fires’ were longest on La Viga and shortest on San Antonio. However, the differences in MFI between mountains were not significant. The only significant difference in MFI among sites was found for ‘all fires’ between SA1 (MFI 7.8) and LV1 (MFI 16.4; P = 0.04).

Several of our sites had pulses of tree regeneration in the past, defined and identified as multiple pith dates of fire-scarred samples clustered within a 30-year period. San Antonio had the fewest pulses of regeneration, with few clusters of pith dates and only three to six trees per cluster (Fig. S1 of the Supplementary material). Pulses were most pronounced in sites on La Viga (LV1, LV2 and LV3). Each of the sites had a pulse of regeneration in the mid-1700s (Fig. 2). Thirteen samples in site LV1 had pith dates between 1745 and 1758, 11 samples in site LV3 had pith dates between 1736 and 1763, and four samples in site LV2 had pith dates between 1741 and 1754. In addition, site LV1 had a pulse of regeneration between 1595 and 1600 (nine samples) and site LV2 had a pulse of regeneration between 1636 and 1662 (13 samples). There was evidence of clumps of regeneration on Rancho Nuevo as well, but there were fewer trees in each pulse (Fig. S2).

Fire synchrony

Across the entire record, in only 6 years did all three mountains record a fire (1622, 1654, 1689, 1785, 1797 and 1838) (Fig. 3) out of 126 total fire years during that period (5%). The years of highest synchrony among sites were 1785 and 1797, when eight of the nine sites recorded fire. The three mountains were not consistent in the timing of fire exclusion. Sites on La Viga were uniform; the last multi-scar fire at all three sites was in 1917. However, sites on Rancho Nuevo had their last multi-scar fires in 1909 or 1952, and sites on San Antonio were the least consistent, with last multi-scar fire dates in 1887, 1918 and 1962 in the three sites. Results of Chi-square tests indicate that the level of synchrony among mountains and among sites is no higher than would be expected by chance (Tables S1, S2 of the Supplementary material). Consistent with the Chi-square results, clustering based on similarity analysis of fire dates among pairs of sites resulted in the strongest affinities being among sites on each mountain. The result is plotted as a dendrogram (Fig. 4).

Fire–climate

La Niña events were associated significantly with the occurrence of ‘widespread’ fire in our study region before 1831 and were associated strongly but not significantly after 1832 (Fig. S3). In an analysis of ENSO association with different levels of fire synchrony on the three mountains over the entire period (1411–1978), years when zero mountains recorded fire were associated significantly with El Niño; years when one or two mountains recorded fire were associated significantly with La Niña, and years when all three mountains recorded fire were not associated significantly with ENSO (Fig. 5).

Discussion

Low fire synchrony

Sites on the three mountains historically had similar fire regimes in terms of fire frequency and seasonality, despite the lack of synchrony of fire dates among mountains. The fire regimes on all three mountains were characterised by frequent surface fire, with little significant difference among sites or mountains. However, fire on the three mountains was highly asynchronous: very rarely did all three mountains record fire in the same year despite a frequent fire regime on each mountain. Our results suggest that at the scale of our study region, fine-scale factors influencing fire predominated. Although ENSO was correlated with fire occurrence over a long temporal scale, it was not strong enough to synchronise fire throughout the region any more than would be expected by chance.

Synchrony in our sites was lower than in comparable settings elsewhere. For example, in the Chiricahua Mountains in southeastern Arizona, two areas (Sara Deming Canyon, Baisan and Morino 2000, also see http://hurricane.ncdc.noaa.gov/pls/paleox/?p=519:1:0:.:P1_STUDY_ID:1945; and Rustler Park, Seklecki et al. 1996) separated by 13 km of rugged terrain shared
16 out of 66 total fire dates (24%) between 1708 and 1894. At a larger scale, a regional analysis of fire dates in the Madrean Archipelago (SE Arizona, SW New Mexico and NW Sonora) revealed that there were 30 years between 1648 and 1886 when at least five of 31 sites (16%) recorded fire (Swetnam 2005). This is a higher level of synchrony, over a much larger region, than we found in our study area. However, synchrony among sites in our study area was comparable to synchrony among sites in El Malpais National Monument in New Mexico, a study location where some sites were separated by lava flows that act as natural barriers. In a 230-year period, 13 fire years (5.7%) coincided at four or more of the nine sites (Grissino-Mayer and Swetnam 1997). In comparison, in a 218-year period at our study sites, 10 fire years (4.6%) coincided at four or more of the nine sites.

![Figure 2. Fire history graph for La Viga: top, LV1; middle, LV2; bottom, LV3.](image)

Horizontal lines represent individual tree samples; solid horizontal lines represent periods when the sample was recording and dashed horizontal lines represent periods when the sample was not recording. Bold vertical tick marks represent precisely dated fire scar dates. Vertical lines to the left represent pith dates and slanted lines to the left represent inside ring dates (i.e. unknown number of years to pith). Grey boxes indicate 30-year periods with pulses of regeneration ($\geq 8$ pith dates).
sites. In another example from north-western Arizona, low synchrony of fire found among sites was probably due to a lack of fuel continuity, with patches of ponderosa pine separated by a matrix of less flammable vegetation types (Ireland et al. 2012).

Although the fire regimes were similar among mountains, there was some variation. MFI for ‘all fires’ and ‘widespread fires’, WMPI and maximum interval were all longer on average in La Viga sites than in sites on the other two mountains. San Antonio tended to have the shortest intervals of the three mountains. The mountain highest in elevation, La Viga, had more pulses of regeneration, which could be evidence of small patches of high-severity fire, but we found no evidence of high-severity fire at the scale of our sites (25 ha) or greater. Brown et al. (2008b) did not consider multi-aged stands with recruitment pulses that overlapped living trees (as was the case at our sites) to indicate evidence of high-severity fire. However, we suggest that small patches of high-severity fire may have opened up gaps within our sites at the scale of <25 ha. We acknowledge the limitations of using pith dates of fire-scarred trees instead of full stand age data to assess recruitment pulses and the possibility of historical high-severity fire, but we believe the results are still useful to report. The fire scars were collected from trees of multi-century age that had survived numerous fires. These scarred, fire-surviving trees represented an average of 40 trees per 25-ha site (357 trees over nine sites), providing evidence that a stand-replacing fire or other disturbance at a patch size of 25 ha had not occurred for at least several centuries.

Several fine-scale factors varied among the three mountains as well, including elevation, topography and forest species composition. First, elevation varied slightly among mountains: sites on La Viga were on average 130 m higher than sites on San Antonio and 244 m higher than sites on Rancho Nuevo. Other studies have found longer fire intervals, more synchronous fires and more stand-replacing disturbance with increasing elevation (Brown et al. 2001; Fule et al. 2003; Margolis and Balmat 2009).

In terms of topography, sites on La Viga and Rancho Nuevo were arranged on steep north-facing slopes, and sites on San Antonio were on three flatter, mostly south-facing sides of a wet meadow. Average slopes varied: San Antonio sites were the least steep with average slopes of 28%, whereas sites on La Viga and Rancho Nuevo averaged 44 and 42% slope. Slope and aspect have both been shown to affect fire history patterns (Gavin et al. 2003, Iniguez et al. 2008). All of these interlinked factors could have had an influence on the local fire regime.

Kellogg et al. (2008) hypothesised that broad-scale controls are stronger in topographically simple landscapes, whereas bottom-up controls are more important in more topographically complex landscapes. This hypothesis was supported by modeling work by Kennedy and McKenzie (2010) using fire scar data, and it is supported by our findings of strong bottom-up controls in a topographically complex area. Flatley et al. (2011) concluded that topography is an important influence on fire but also that it can be overridden by climate. In our study region, there were only 6 years in which all three mountains recorded fires, suggesting that here the synchronising effect of climate has rarely overridden the strong influence of the complex topography.

**Human influence on fire occurrence**

This area has a long history of human use of the forest (Ortega-Jiménez 2008); certainly humans have used fire in this region.
for various reasons over centuries. However, we do not have information about how many fires were started by humans (rather than lightning) throughout history, nor whether human ignition patterns were different among mountains. We also do not know the full history of logging on these mountains, although we know from plot measurements (L. L. Yocom, P. Z. Fulé, D. A. Falk, C. García-Domínguez, E. Cornejo-Oviedo, P. M. Brown, J. Villanueva-Díaz, J. Cerano and C. Cortés Montaño, unpubl. data) that the tree species most often cut was different on Rancho Nuevo from that on San Antonio and La Viga. The majority of stumps on Rancho Nuevo were from *Pseudotsuga menziesii* whereas *P. hartwegii* was the most commonly cut species on San Antonio and La Viga. This reflected the variation in dominant tree species on the three mountains. All three mountains had roads leading to the top. We saw evidence of grazing on San Antonio and seasonal homes on San Antonio and La Viga, but we lack information about current or historical grazing levels. All three mountains were close to small human population centres in the valleys below and have doubtless been visited and used for centuries (Ortega-Jiménez 2008). We did not see an increase in fire occurrence in the fire scar record that we can link to changed land use (e.g. Donnegan et al. 2001) or changes in seasonality that we can attribute to human fire ignitions (e.g. Grissino-Mayer et al. 2004).

The only change to the fire regime that we could attribute to human activity was the decrease in fire that began between 1887 and 1962. The lack of synchrony in the onset of fire exclusion was unusual in comparison to many fire history studies from the western United States, where the onset of fire exclusion was consistent not only across study areas but fairly so across much of the western United States because of the onset of grazing, logging and fire suppression. In other areas in Mexico, the cessation of frequent fire was coincident with the formation of ejidos, which are rural communities living on and managing commonly held land, and with an increase in livestock grazing (Heyerdahl and Alvarado 2003; Yocom et al. 2010, Poulos et al. 2013). In the region of our study sites, there was a patchwork of ownership, with some areas under ejido management and other areas privately owned. *Ejido* formation, which took place in the mid- to late-1930s in this area, would not be expected to align with the dates of last fires across all study sites given that ownership varied across the mountains; and that is indeed what we saw: the dates of last fires spanned several decades. In this case, as elsewhere in Mexico, human influence on fire cessation varied at a fine scale.

**The role of ENSO**

Despite the lack of fire synchrony among the three mountains, there was a relationship between climate and fire occurrence in our study region. La Niña events were associated with fire occurrence over time. There was a change in the relationship in the 1830s at this study area, but it was nuanced: La Niña events were still strongly associated with fire occurrence after the 1830s although the association was no longer significant at the 95% confidence level (Fig. S3). This contrasted with previous results from north-eastern Mexico, where at Peña Nevada after the 1830s there was no relationship at all between ENSO and fire (Yocom et al. 2010). Our results led us to speculate that these

**Fig. 5.** Superposed epoch analysis showing departure from the mean value of NINO3 SST (sea surface temperatures; Cook 2000) years in which 0 (a; \(n = 416\)), 1 (b; \(n = 113\)), 2 (c; \(n = 22\)), and 3 (d; \(n = 6\)) mountains recorded fire (1411–1978). Typically in this region, positive NINO3 values tend to be correlated with above-average precipitation and negative NINO3 values tend to be correlated with below-average precipitation. Fire years are indicated by 0 on the x-axis, and values are also given for 5 years before fire years (negative values) and 2 years after fire years. Black bars are those that pass the 95% confidence interval. Here, NINO3 is a unitless index.
study sites, being farther north, are outside the transition zone where ENSO effects change over time. To investigate this point fully, a more extensive network of climate reconstructions and fire-climate sites is needed in this region.

The high frequency of fire in this study region indicated that fires do not burn only in the most extreme climate years. A fire occurred somewhere in the nine sites every 3 years or less in the period common to all nine sites. Climatically, opportunities for fires to burn were fairly common; years with NINO3 values equal to or less than the average NINO3 value for all fires occurred in 140 out of 381 years (36.7%) between 1622 and 2002. This may help explain why fire synchrony was so low among mountains.

Our results highlight the importance of scale in describing fire regimes, and suggest that we can use fire history to understand the controls on complex ecosystem processes. In this region, conditions or fuel continuity were typically not conducive for fire spread from mountain to mountain; the non-contiguous nature of this landscape for fire could indicate a non-contiguous pattern for other processes as well. The asynchronous fire dates but similar fire regimes among the mountains suggest an independent but ‘convergent’ fire regime on each mountain: before fire exclusion, forests on these mountains burned frequently but not simultaneously. Fires were asynchronous on the three mountains despite their close proximity. This emphasises the importance of limiting inferences about a heterogeneous region based on a small sampled area. Finally, fire exclusion was not synchronous and occurred in this small region over a period of 75 years. Any management activities in this region should take into account the spatial heterogeneity in disturbance history among sites and mountains.

Acknowledgements

We thank local ejidos and landowners for permission to work on their land. Armando Becvort, Ericha Bigio, Walker Chanceller, Julian Charles, Vicenta Constante Garcia, Oswaldo Turlhan Medina and Cameron Fule provided valuable assistance in the field. Many thanks also to Don Normandin, Charles Machula and other staff and students at the Ecological Restoration Institute. The pilot study in site SA1 in 2001 was done as part of the North American Dendroecological Fieldweek. Two anonymous reviewers and an associate editor made suggestions that greatly improved the manuscript. This research was supported by the National Science Foundation (DEB-0640351) and the Ecological Restoration Institute at Northern Arizona University.

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